**A COMPARISON OF THE WIDE GAP
AND NARROW GAP RESISTIVE PLATE CHAMBER**

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Abstract

In this paper we study the performance of a wide gap RPC and compare it with that of a narrow gap RPC, both operated in avalanche mode. We have studied the total charge produced in the avalanche. We have measured the dependence of the performance with rate. In addition we have considered the effect of the tolerance of gas gap and calculated the power dissipated in these two types of RPC. We find that the narrow gap RPC has better timing ability; however the wide gap has superior rate capability, lower power dissipation in the gas volume and can be constructed with less stringent mechanical tolerances.

1. INTRODUCTION

The Resistive Plate Chamber using bakelite plates was developed some years ago by Santonico et al. [1]. Basically it is a very simple detector; a gas volume, 2 mm thick, is contained between two resistive plates. An electric field is generated across this gap by applying a voltage to electrodes on the outer surface of the plates. A through-going charged particle creates electron and positive ion pairs. The electrons multiply by avalanching in the high electric field. Depending on the applied voltage, either the avalanche signal can be detected (avalanche mode operation) or the avalanche initiates a spark break-down (spark mode operation; some authors refer to this mode as streamer mode). The resistance of the plates limits the intensity of the spark. At this moment, experiments using RPCs operate in spark mode; however in spark mode operation, the efficiency of the RPC drops quickly with rate [2,3] since the surface of the resistive plates becomes charged and reduces the electric field across the gas gap. The full electric field is restored by current flowing through the resistive plates.

A possible route to high rate operation is to reduce the amount of charge produced by the gas-gain process initiated by the through-going particles; thus one attempts to operate the RPC in avalanche mode rather than spark mode. The problem with avalanche mode operation is that there is a certain probability that a spark also occurs; this spark generates a very large signal. In avalanche mode operation the RPC is equipped with many sensitive preamplifiers, thus any spark will affect a large area of the RPC. There are two methods to reduce the effect of sparks. The first is to quench the spark by using a high fraction of u.v.-absorbing gas, such as freon [4,5]. The second method is to increase the size of the gas gap[6], which decreases the probability of a spark. Here we will look at the results of these techniques; we have made a detailed comparison of a narrow gap (2 mm) RPC operated with a gas mixture containing 85% freon and a wide gap (8 mm) RPC operated with a freon-free gas mixture.

In discussions regarding the operation of RPCs, the magnitude of the fast signal generated by the movement of electrons is often quoted. However, we are concerned with the total charge produced inside the gas gap, since it is this charge in its totality that has to be neutralised by a current flow through the resistive plates; this current flow causes a voltage drop across the resistive plates and thus limits the operation at high rates. We discuss the fast signal and the expected total amount of charge produced in the RPC. We show measurements from the two types of RPC mentioned above. We find that operating the chamber with the same threshold, the average charge of the fast signal is much lower for

the 8 mm than for the 2 mm gap RPC; this gives the wide gap RPC a superior rate capability; in addition less power will be dissipated in the gas volume.

2. THE FAST SIGNAL AND TOTAL CHARGE

The fast signal produced by a gaseous avalanche is due to the movement of the electrons towards the anode. The ratio of the fast signal (due to the movement of electrons in the avalanche) to the total signal is $1/\alpha D$; where α is the first Townsend coefficient and D the gap width. This has been discussed previously [7], where we calculated that the integrated charge of the fast signal is 7% of the total electron charge produced in the avalanche. The reason for this is clear, to obtain the full signal one has to wait for all the positive ions to drift to the cathode. Thus for an avalanche that produces 1.5 pC of electrons, the fast signal will be 100 fC; additionally there exists 1.5 pC of positive ions, which will be attracted to the cathode.

Freon is an electronegative gas, and thus there is a certain probability that an electron, instead of having an ionising collision and participating in the avalanche process, is captured by the freon molecule and forms a negative ion. The number of electrons in an avalanche is given by: $N = N_0 e^{\alpha x}$, where x is the distance, N_0 is the original number of electrons and α is the first Townsend coefficient. In the presence of an electronegative gas the Townsend coefficient is replaced by the effective Townsend coefficient $\alpha' = \alpha - \eta$, where η is the attachment coefficient. This has two consequences; the first is that commonly α' increases linearly with electric field as discussed by Qiu et al.[8]; the second is that negative ions are created. These negative ions do not participate in the production of the fast signal; however depending on the actual values of these coefficients (α and η) a large number of negative ions can be produced, in some cases more than the number of free electrons arriving at the anode. Thus, with freon one may expect an increase in total charge without a corresponding increase in the magnitude of the fast signal.

3. EXPERIMENTAL PROCEDURE AND COSMIC TESTS

The RPCs that we tested were of simple construction. The 2 mm gas gap chamber was constructed with 1.2 mm thick melamine-phenolic-melamine* resistive plates. Pad electrodes of dimension 24 x 24 cm² (which defined the active area) were mounted on the outer surfaces of the plates. The resistive plates were held flat by two sheets of 2 cm thick Plexiglas. The cathode was attached via a 1 M Ω resistor to a negative high voltage power supply and the signal read out via a 1 nF high voltage capacitor. The other electrode, the anode, was held at ground potential either by the 50 Ω input impedance of an amplifier or

* The Melamine laminate was produced by Argolite, S.A.

the 1 M Ω input impedance of the oscilloscope. The cathode was coupled to a fast current amplifier followed by an ORTEC shaping amplifier; this signal fed a discriminator, the output of which we associated with gas avalanches. The anode signal was either amplified by a factor 2 and then passed to a discriminator with a threshold of 150 mV (i.e. detection of sparks) or fed directly to a digital oscilloscope with 1 M Ω input impedance for the charge measurement (described below). The movement of charge between the anode and cathode induce opposite going signals on these two electrodes. There is a large capacitive coupling between the anode and cathode. Therefore the induced signal on the anode, for example, is reduced by the induced cathode signal transmitted to the anode via this capacitance; similarly the cathode signal is also reduced. This effect depends on the impedance between the electrode and ground. In our measurements we find a reduction factor of 2.5 when the anode is connected via the 1 M Ω to ground. For the beam test (discussed later) the pickup-strips (i.e. the anode) were connected to ground via the low impedance of the pre-amplifiers, thus the cathode signal was unaffected.

Using cosmic ray muons we have made various measurements in the laboratory. We have measured the efficiency plateau for both spark mode and avalanche mode operation. The "avalanche" discriminator would fire on signals above 100 fC, while the "spark" discriminator would fire on signals greater than 10 pC. Figure 1 shows two plateau curves for freon content of 35% (a) and 85% (b); in addition we show the dark current. The balance of the gas mixture was Argon/isobutane in a 6:4 ratio. Additionally in all our tests we bubble the gas through water at 10°C to add 1% water vapour to the mixture; this was to keep the resistivity of the electrodes constant in time[9]. As discussed by Duerdoth et al.[5] the magnitude of the fast signal generated by sparks is reduced with increasing freon concentration. Extrapolating the results of Duerdoth, one predicts that at ~80% freon concentration, the magnitude of the spark signal is similar to that of the avalanche signal. For the 85% freon data, the curve labelled sparks in the plateau curve can in reality be considered as "extra large" avalanches.

We measure the total charge produced in the RPC at various voltages along the plateau curve. For this measurement the anode is directly connected to a digital oscilloscope; a typical display is shown in figure 2. The fast step is due to the electrons; the slow ramp is due to the positive ions drifting towards the cathode, and flattens out when the ions arrive at the cathode. The total capacitance has been previously measured, thus the total voltage swing can be equated to a charge. For each coincidence from the cosmic ray telescope, we record the magnitude of the fast signal (as observed by the fast current amplifier attached to the cathode) and the total voltage swing on the anode. Events where the fast amplifier produces a large saturated pulse we label as 'sparks'. We plot the average of the total charge produced by avalanches and sparks versus voltage in figure 3, for the two

freon mixtures shown in figure 1. Figure 4 shows the voltage that corresponds to the knee of the efficiency plateau as a function of freon concentration. The chamber that we tested in the test beam had a slightly larger gas gap and needed an increased high voltage. We also show the data from Duerdoth et al.[5] and Bacci et al.[10]; the results of Bacci et al. appear to be inconsistent with our data and the data of Duerdoth et al.

We have constructed and tested a chamber with a similar construction to the above 2 mm gap chamber, but with an 8 mm gas gap. The remainder of this paper is concerned with comparative tests on these two chambers. In figure 5 we show the plateau curve with a gas mixture of 42% Argon, 39% CO₂ and 19% DME. Figure 6 shows the average charge per avalanche as a function of voltage.

We have also measured the ratio of charge contained in the fast signal to the total charge, using the technique above. As stated above this ratio is simply $1/\alpha D$; this gives 8.6% for a gas gain of 10^5 reducing to 6.2% for a gas gain of 10^7 (the gas gain is defined as $e^{\alpha D}$). In figure 7 we plot our measurement of this ratio as a function of the fast signal charge for the 8 mm chamber; the shown errors are statistical. In figure 8 we show the ratio for the 2 mm gap chamber for two freon mixtures (other intermediate freon mixtures give very similar results). Since there is a production of negative ions due the freon, we would expect that this ratio should be smaller than the calculated 7-10%. For small avalanches the ratio is indeed smaller ($\sim 2\%$), but as can be seen this ratio increases for large avalanches.

4. MEASUREMENTS WITH TEST BEAM

We tested the RPCs in the T9 test beam in the CERN East Hall. The 2 mm gas gap RPC was constructed with resistive plates of 1.2 mm thick melamine-phenolic-melamine laminate. This chamber was a different chamber than the one used for the cosmic ray tests; it had a gas gap of 2.35 mm; however for brevity we will still refer to it as the 2 mm gap chamber. We tested this chamber with the 85% freon mixture in avalanche mode. The 8 mm gas gap chamber had resistive plates of melamine-phenolic 0.9 mm thick. For both chambers we added 1% water vapour to the gas mixture by bubbling the gas through water at 10°C; the bulk resistivity of the melamine laminate (in presence of this water vapour) was between 10^{10} and $10^{11}\Omega$ cm. One resistive plate was equipped with pick up strips on a 15 mm pitch, while the other plate was a single pad electrode attached via a 1 M Ω resistor (in later tests this was reduced to 15 k Ω) to the high voltage power supply. The strips form the anode plane; initially we had a gap of 2.5 mm between strips, however this led to reduction in efficiency. We reduced this gap to 250 μ m and recovered the lost efficiency. We used a defocused beam covering the whole active area. A 4 x 4 cm² scintillator selected the central region of the chamber under test. We used this counter for the rate measurements. A larger 12.5 x 12.5 cm² scintillator measured a flux about a factor 2 less

than the central $4 \times 4 \text{ cm}^2$. In figure 9 we show the variation of efficiency of the 2 mm RPC during the spill for three rates with a chamber voltage of 19.3 kV. The curves are 2nd order polynomial fits to guide the eye. For the efficiency versus rate measurements, we gated the spill to the time interval 200 to 300 ms. Figure 10 shows the efficiency plateaux for the 2 mm chamber for various particle fluxes; Figure 11 shows the efficiency plateaux for the 8 mm chamber. Note that a higher voltage was required for this chamber than that shown in figure 1 since the gap is slightly larger. In figure 12 we show the efficiency of both the 8 mm and 2 mm RPC as a function of rate. The efficiency plateau is practically unchanged for the 8 mm chamber for rates up to 2.5 kHz/cm^2 . However, for the 2 mm chamber not only does the efficiency decrease with rate, but also the efficiency plateau changes shape. Thus for high rates the maximum of efficiency occurs at a higher applied voltage.

In figure 13 we show the charge spectra of the 2 mm and the 8 mm RPC; the data have been taken at 100 Hz/cm^2 . The electronics (fast current preamplifiers followed by time-over-threshold discriminators) attached to the chamber were the same in each case; we operated at a threshold of $\sim 50 \text{ fC}$. In both cases one can see that the most probable value is lower than the mean value, due to the long tail. The 2 mm chamber has a far larger average charge (9.1 pC) than the 8 mm chamber (1.8 pC). This is due to the increased dynamic range of gain that one has with a 2 mm gas gap [6]. In figure 14 we show the average charge (fast signal) as a function of the applied voltage for the 2 mm chamber and the 8 mm chamber, exposed to a rate of 100 Hz/cm^2 . For the 2 mm chamber we show two curves. The lower curve is obtained from the average value of the histograms similar to that shown in figure 13; however this is an underestimate due to the saturation of the preamplifier. The upper curve is calculated by using the 50% point of the integrated histogram and normalising to 10 pC at the knee voltage; this is insensitive to the saturation of the preamplifier, but does assume that the charge spectrum has the same shape for increasing applied voltage.

Time-over-threshold discriminators are attached to each strip on the chamber; the read out is with a LeCroy CAMAC TDC 2277, which records the time of both the leading and trailing edge of the pulse. The rise time of the pulse depends on the time needed for avalanche formation; the fall time depends on the capacitance of the pick up strips and electronics. The upper histograms in figure 15 show the time distribution the leading-edge, the trailing-edge and the average of these for the 2 mm chamber; the lower histograms show the distributions for the 8 mm chamber. These measurements correspond to 100 Hz/cm^2 . The absolute value of the timing depends on the drift speed of the electrons in the gas and the gap width; the signal from the 2 mm chamber occurs $\sim 60 \text{ ns}$ earlier than the 8 mm chamber. However what is significant, for example for triggering at LHC, is the width of

the distribution. As expected, the narrow gap RPC gives better timing. The average of the leading-edge and trailing-edge timing, which corresponds to a slewing correction, gives the best result and should be used, with the appropriate electronics (for example, constant fraction discriminators).

5. DISCUSSION

From the previous results it is clear that the narrow gap RPC has superior timing compared to the wide gap RPC; however the 8 mm RPC has superior rate capability. It should be noted that the 2 mm and 8 mm gas gap are the extremes. Recently we have started to test 5 and 6 mm gas gap; these chamber appear to have both excellent time resolution and rate capability. This will be discussed in detail in a later paper.

Besides these straightforward results, two other factors must also be taken into account: these are the precision of the gas gap and the power dissipated in the gas volume. The tolerance in the distance between the parallel plates (exact width of the gas gap) will depend on the size of the chambers and the number of spacers used. The RPCs that we use for our tests are small ($30 \times 30 \text{ cm}^2$) and the tolerance of the gap is tight ($\sim \pm 25 \text{ }\mu\text{m}$). For large area detectors, as will be used for LHC, the allowed limits for this tolerance must be relaxed, and $\pm 100 \text{ }\mu\text{m}$ is a realistic lower limit. However, the gap variation results in a variation of the electric field inside the chamber, since the voltage applied on the plates is constant. For example, for the 8 mm chamber operating at 17 kV (21.25 kV/cm), a variation of $\pm 100 \text{ }\mu\text{m}$ translates into a change of the field by $\pm 250 \text{ V/cm}$. The knee of the efficiency plateau (fig. 10) is at 16.7 kV. To allow for a gap variation of $\pm 100 \text{ }\mu\text{m}$, the chamber should have stable operation in the range of 16.7 to 17.3 kV. From figure 11 this seems to be the case.

For the 2 mm RPC operating at 19 kV (95 kV/cm), a variation of $\pm 100 \text{ }\mu\text{m}$ translates into a change of the field of $\pm 4500 \text{ V/cm}$. The knee of the efficiency is at 18.8 kV; therefore, in order to allow for $\pm 100 \text{ }\mu\text{m}$ variations in the gap width, the chamber should be operated at 19.8 kV, and should be stable in the 19 to 21 kV range. From fig. 10 one can see that the plateau for the 2 mm RPC is extended; however, as one can see from figure 14, inevitably the signals have a higher average charge.

Another factor which has to be considered is the power drawn by the detector from the high voltage supply. For the 2 mm gap RPC in order to compensate for variations in the exact gap width, one has to operate at 1000 V above the knee of the plateau. From fig 14 one finds that the average induced fast charge is 20 pC. This is only 7% of the total induced charge (or less, see figure 8), thus the total induced charge per avalanche (due to one detected particle) is 300-600 pC. For a rate of 1 kHz/cm^2 , this means the total charge

per second and per m^2 is equal to 6-12 mC [11] i.e. a current of 6-12 mA/m^2 . The power drawn per m^2 (with 20 kV applied) is calculated to be in the range 120-240 W/m^2 . We have measured the current drawn by the chamber during our test runs and find it consistent with the above calculation.

Following the same logic, if we operate the 8 mm gap RPC at 200 V above the knee of the plateau, namely at 17 kV, the average fast charge (from fig. 14) will be 2 pC. Therefore the average total induced charge will be 30 pC. For a rate of 1 kHz/cm^2 the current will now be 0.6 mA/m^2 . The power drawn per m^2 therefore will be 17 kV $\times$ 0.6 mA/m^2 = 10 W/m^2 ; i.e. a factor of 10 less than the 2 mm gap RPC.

From the above calculations it is clear that the current and therefore the power drawn by the RPC for the kHz/cm^2 range has to be given serious consideration. The problem of power limitation could be solved by using more powerful power supplies; however this does increase the expense of the system; also, for such values of power one has to start considering the amount of heat generated in the gas volume. In addition, ageing effects are often related to the amount of deposited charge; if this is so, then clearly the lower charge observed with the wide gap RPC would be an advantage. Are there any easy solutions to this problem of power? One obvious way would be to have more sensitive pre-amplifiers and work at lower gas gain. We are investigating this possibility, however we find the RPC is somewhat a noisy device; at the thresholds we are using (~ 50 fC) we believe that the principal cause is the flow of current through the resistive plate itself, and thus different resistive plate materials may generate less noise, allowing a lower threshold to be used. Assuming that one can reduce the threshold, it is not clear that one makes any significant gain with the 2 mm gap chamber. The reasons are: first, one has to sit well above the knee of the plateau to allow for variations of the gas gap (discussed above); the second reason is that when one works with an electronegative gas mixture, the effective Townsend coefficient, α' , which defines the avalanche gain, is the difference between the Townsend coefficient, α , and attachment coefficient, η . Thus at low gas gains (low $\alpha' = \alpha - \eta$) the Townsend coefficient and attachment coefficient become close in value. Any small decrease in electric field (due to variation of gas gap, surface imperfections, deposited charge, etc.) will result in an increase of the attachment coefficient and a decrease of the Townsend coefficient; thus α' becomes negative and no avalanche is produced at all. Since the wide gap RPC operates without the use of an electronegative gas, lower electric fields result in smaller avalanches; in this case a lower threshold would help. Another possibility would be to reduce the dynamic range of the charge spectrum; a heavy gas which has a high number of primary ionisation clusters per mm would help achieve this.

6. CONCLUSION

From the results presented above, it is clear that the narrow gap RPC has better timing compared to the wide gap RPC; however the wide gap RPC has superior rate capability. This is due to a lower dynamic range of avalanche charge, and thus a lower average charge being produced. Thus the power dissipated in the gas gap in the wide gap RPC is also a factor 10 lower than the narrow gap RPC. This problem of power dissipation may be a deciding criterion for LHC operation. In addition, the wide gap RPC can tolerate a $\pm 100\text{ }\mu\text{m}$ gap variation - whereas the performance of the 2 mm chamber is compromised. Recently we have started to test wide gap RPCs with 5 and 6 mm gas gap. Initial results are very promising, indicating excellent timing and rate capability.

Acknowledgements

The availability of test beams at CERN is vital for this type of R&D. This is enhanced by the excellent services of the PS division that makes the use of the CERN East Hall test beams a pleasure. We thank everyone involved that makes this possible. Also, we thank Dr. J.G. McEwen for careful reading the manuscript and thus improving the clarity of this paper.

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FIGURE CAPTIONS

- Figure 1. Efficiency plateau of a 2 mm gap RPC measured with cosmic ray muons for 34% Freon (upper plots) and 85% Freon (lower plots). The balance of the gas was Argon:Isobutane in a ratio of 6:4, additionally the gas was bubbled through water at 10°C to add 1 % water vapour. We also show the probability for sparks and the dark current. The lines are added to guide the eye.
- Figure 2. Typical anode signal from the 8 mm RPC as measured by a digital oscilloscope (used for the measurement of the total charge).
- Figure 3. Mean value of the total charge of avalanches and sparks as a function of the high voltage for 34% Freon (upper plots) and 85% Freon (lower plots) for a 2 mm gap RPC. Error bars (only shown when larger than the plot symbol) are statistical. The data for 'spark' and 'avalanche' is only for cases where the signal is classified as one or the other, the average includes zero when we observed no signal at all. The line is a linear fit to the average.
- Figure 4. The voltage corresponding to the 'knee' of the efficiency plateau as a function of freon concentration for a 2 mm gap chamber. We compare our measurements with Duerdath et al.[5] and Bacci et al. [10]. We show a range of values for our 2.35 mm gap chamber corresponding to various values measured over a several month period in a test beam. The lines are linear fits to the data.
- Figure 5. Efficiency plateau measured with cosmics for an 8 mm gap RPC (gas composition : Ar 42%, CO₂ 39%, DME 19% bubbled through water at 10°C). In addition to the total efficiency, the probability for sparks and the dark current are shown. The lines are to guide the eye.
- Figure 6. Average charge as a function of the high voltage for the 8 mm RPC. The range of voltage was chosen to be around the knee of the plateau curve shown in figure 5. The line is an exponential fit.
- Figure 7. Ratio of fast to total charge as a function of the charge of the fast signal for the 2 mm RPC, the gas mixture contains freon. The error bars are statistical only.
- Figure 8. Ratio of fast to total charge as a function of the charge of the fast signal for the 8 mm RPC, the gas mixture is freon-free. The error bars are statistical only.
- Figure 9. Efficiency during spill for 3 different rates for the 2 mm RPC. The curves are 2nd order polynomial fits to guide the eye. The flux of particles was constant between 100 and 350 ms; we defined a time slice between 200 and 300 ms for the efficiency measurements presented in figures 10 and 11.
- Figure 10. Efficiency plateau for the 2 mm RPC for 4 different rates. The lines are to guide the eye
- Figure 11. Efficiency plateau for the 8 mm RPC for 4 different rates.
- Figure 12. Efficiency versus rate for the 2 mm and the 8 mm RPC. The data points were extracted from figures 10 and 11 for a fixed applied voltage to the chamber. The lines are linear fits to the data.

- Figure 13. Distributions of the charge magnitude of the fast signal for the 2 mm RPC and the 8 mm RPC, exposed at 100 Hz/cm².
- Figure 14. Average charge of the fast signal as a function of the high voltage for the 2 mm RPC and the 8 mm RPC. Two values are shown for the 2 mm chamber. The lower value corresponds to the mean of histograms similar to that shown in figure 13. This is an underestimate, the higher points are obtained from the 50% value of the integrated histogram. The 8 mm chamber did not produce signals large enough to saturate the pre-amplifier, and thus the mean value is not an underestimate.
- Figure 15. Time distributions corresponding to the time of the leading-edge, trailing-edge and the average of the leading and trailing-edges. The upper three histograms refer to the 2 mm RPC; the lower histograms to the 8 mm RPC. This data was taken at the knee of the efficiency plateau, at 100 Hz/cm².

Figure 1

Figure 2

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Figure 4

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Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

time [ns] →